Higgs Physics at Future e^+e^- Colliders

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Overview of Future e^+e^- Facilities

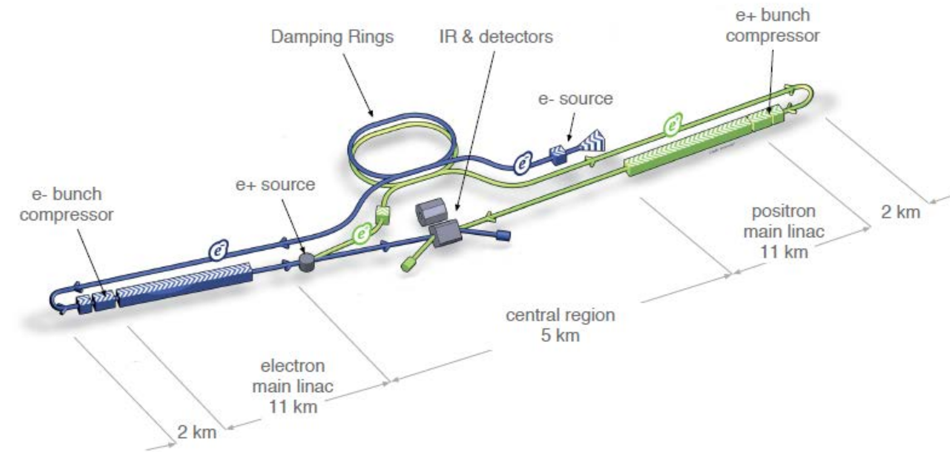
ILC International Linear Collider

e^+e^- linear collider with SCRF linac

$250 \le \sqrt{s} \le 1000$ GeV

31 km length ($\sqrt{s} \le 500$ GeV)

49 km length ($\sqrt{s} = 1000$ GeV)



CLIC Compact Linear Collider

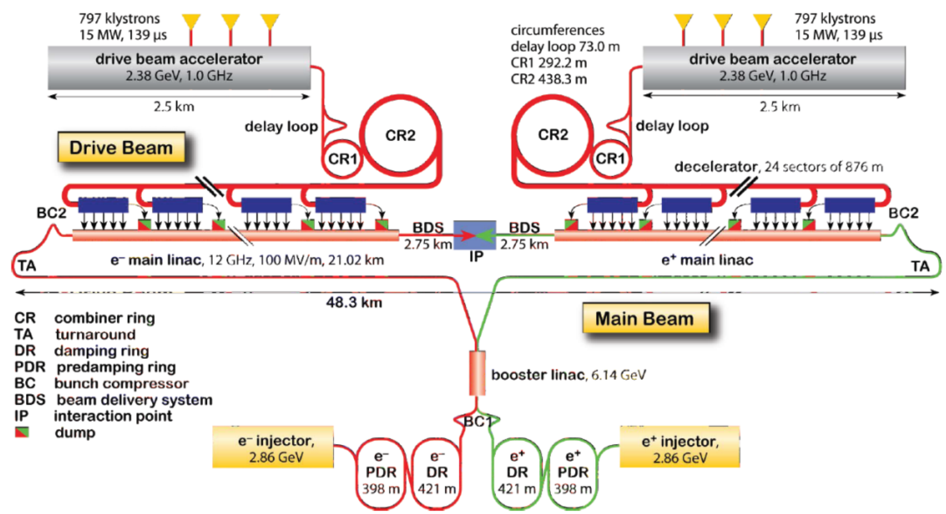
e^+e^- linear collider with X-Band linac

RF powered by a 2nd drive beam

$350 \le \sqrt{s} \le 3000$ GeV

13 km length ($\sqrt{s} = 500$ GeV)

48 km length ($\sqrt{s} = 3000$ GeV)



FCC Future Circular Collider at CERN,   80 -- 100 km circumference tunnel

FCC-ee Future Circular Collider, e^+e^- mode

(Formerly known as TLEP)

$91 \leq \sqrt{s} \leq 350$ GeV

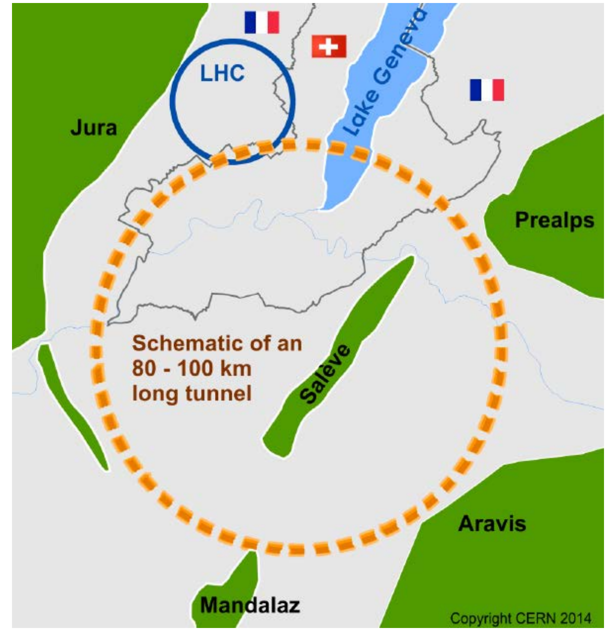
FCC-he Future Circular Collider, pe^- mode

$3.5 \leq \sqrt{s} \leq 4.9$ TeV

FCC-hh Future Circular Collider, pp mode

Known generically as VLHC

$\sqrt{s} = 100$ TeV



Circular collider study in China with 50 km circumference tunnel:

CEPC Circular Electron Positron Collider

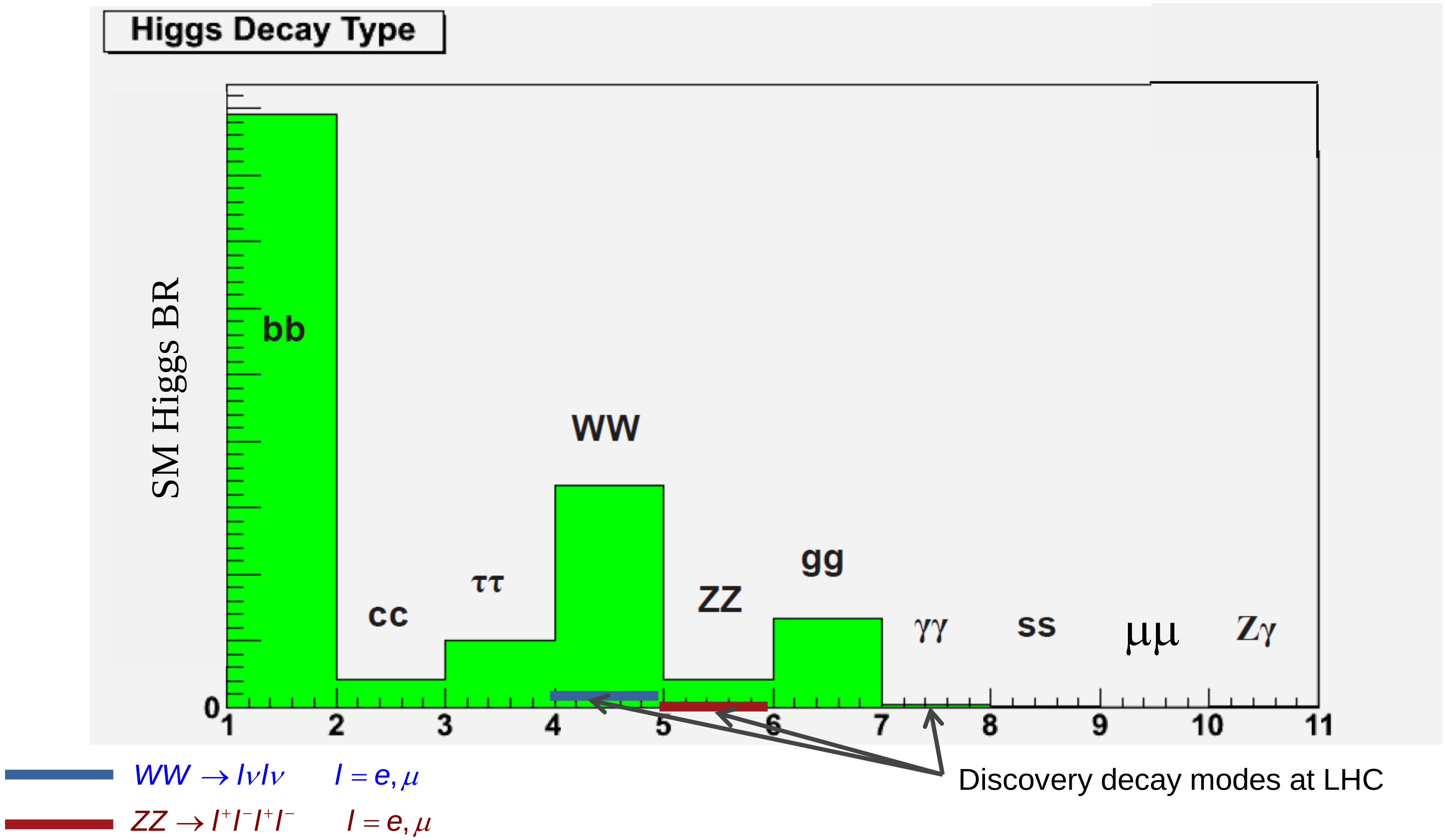
$\sqrt{s} = 240$ GeV

SppC Super proton proton Collider

$50 \text{ TeV} \leq \sqrt{s} \leq 70$ TeV

Higgs Coupling Measurements at e^+e^- Colliders - Generalities

- All background is electroweak.
- Roughly, the detection efficiency is independent of decay mode $\Rightarrow \Delta(\sigma \bullet BR) / \sigma \bullet BR \propto 1/\sqrt{BR}$
- The Higgs recoil measurement of $\sigma(e^+e^- \to ZH)$ provides model independent measurements of the Higgs BR's and Γ_{tot}



Model independent global coupling fit using 32 $\sigma \bullet BR$ measurements Y_i and σ_{ZH} measurement Y_{33}

$$\chi^2 = \sum_{i=1}^{i=33} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 ,$$

$$Y_i' = F_i \cdot \frac{g_{HZZ}^2 g_{Hb\bar{b}}^2}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g_{HWW}^2 g_{Hb\bar{b}}^2}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g_{Htt}^2 g_{Hb\bar{b}}^2}{\Gamma_0}$$

$$F_i = S_i G_i \quad \text{where } S_i = \left(\frac{\sigma_{ZH}}{g_Z^2}\right), \ \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}\right), \ \text{or } \left(\frac{\sigma_{t\bar{t}H}}{g_t^2}\right), \ \text{and } G_i = \left(\frac{\Gamma_i}{g_i^2}\right).$$

The cross section calculations S_i do not involve QCD ISR.

The partial width calculations G_i do not require quark masses as input.

We believe that the total theory errors for S_i and G_i will be at the 0.1% level in 10-15 years.

Overview of Higgs Physics at e^+e^- Colliders for

$\sqrt{s} = 250$ GeV (ILC, FCC-ee,CEPC)

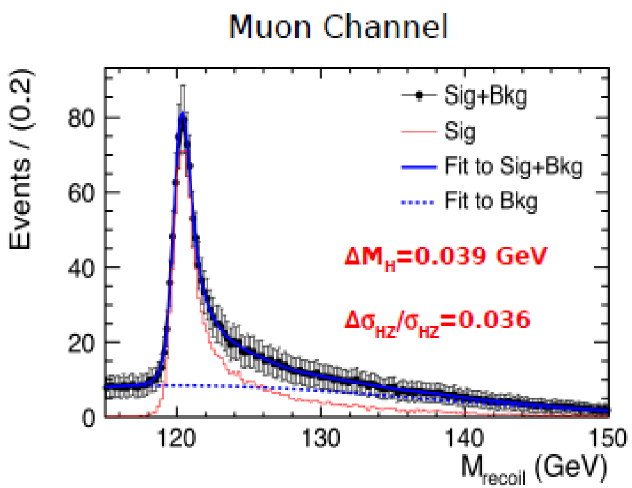
$\sqrt{s} = 350$ GeV (ILC, CLIC, FCC-ee)

$\sqrt{s} = 500$ GeV (ILC, CLIC)

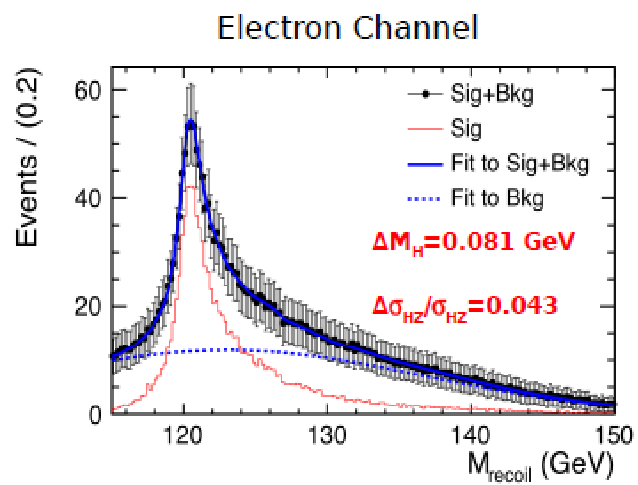
$\sqrt{s}$=1000 GeV (ILC, CLIC)

$$\sigma(e^+e^- \to ZH) \qquad \sqrt{s} = 250 \text{ GeV}$$

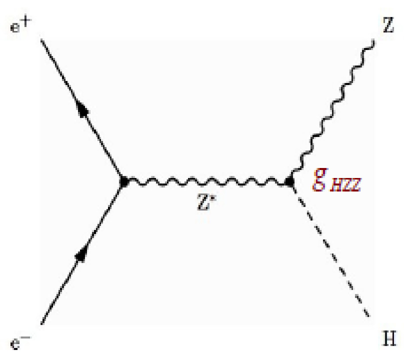
Higgs Recoil Measurement of Higgs Mass and Higgstrahlung Cross Section



Very Precise Measurement
S/B = 8 in Peak Region



Less Precise
Bremsstrahlung in detector material



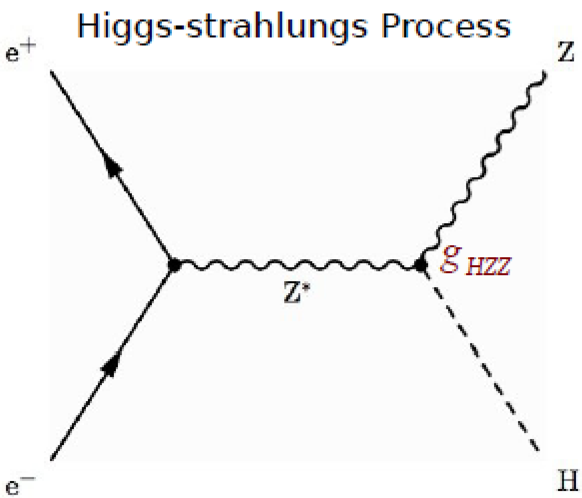
ILC: $\Delta M_H = .032$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=2.5% for L= 250 fb^{-1}

$\Delta M_H = .015$ GeV, $\Delta\sigma_{HZ} / \sigma_{HZ}$=1.2% for L=1150 fb^{-1}

$$\sigma_{HZ} \sim g_{HZZ}^2$$

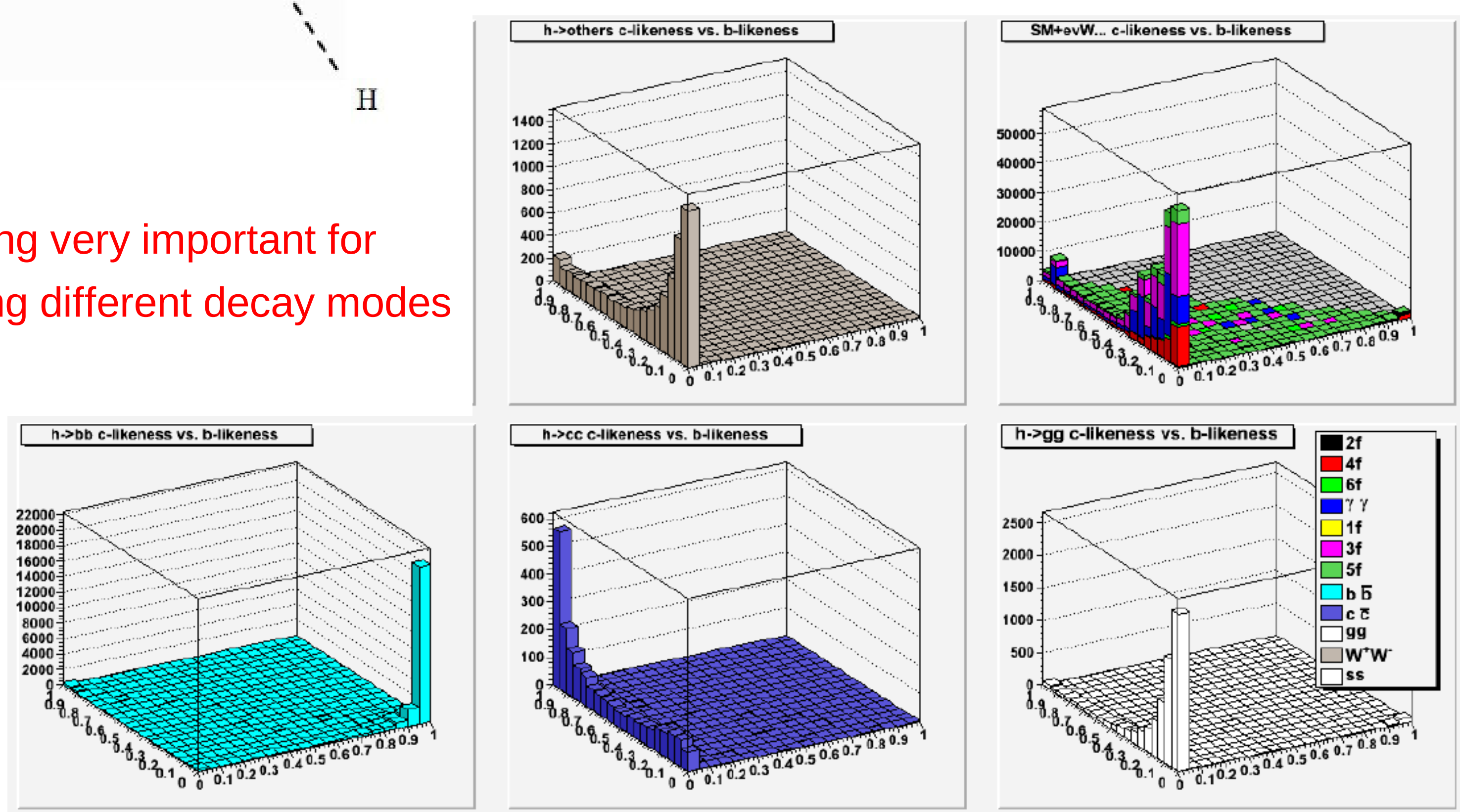
$$\Rightarrow \Delta g_{HZZ} / g_{HZZ} = 1.3\% \ (0.6\%) \text{ for L=250 (1150) fb}^{-1}$$

$\sigma \times$ BR measurements using $e^+e^- \to ZH$ $\sqrt{s} = 250$ GeV



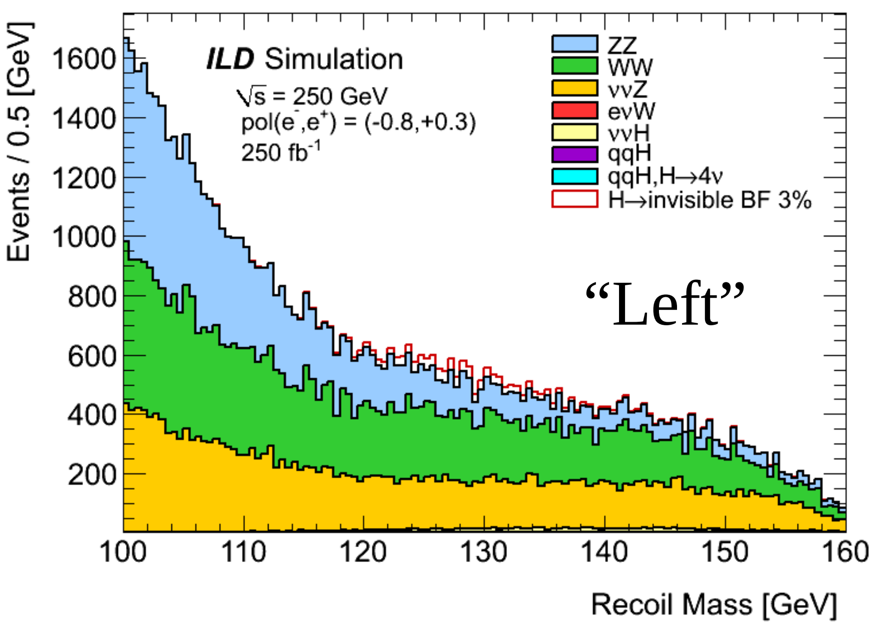
All Z decays are used for measurement of $\sigma \times$ BR. These include $Z \to qq$ and $Z \to \nu\nu$.

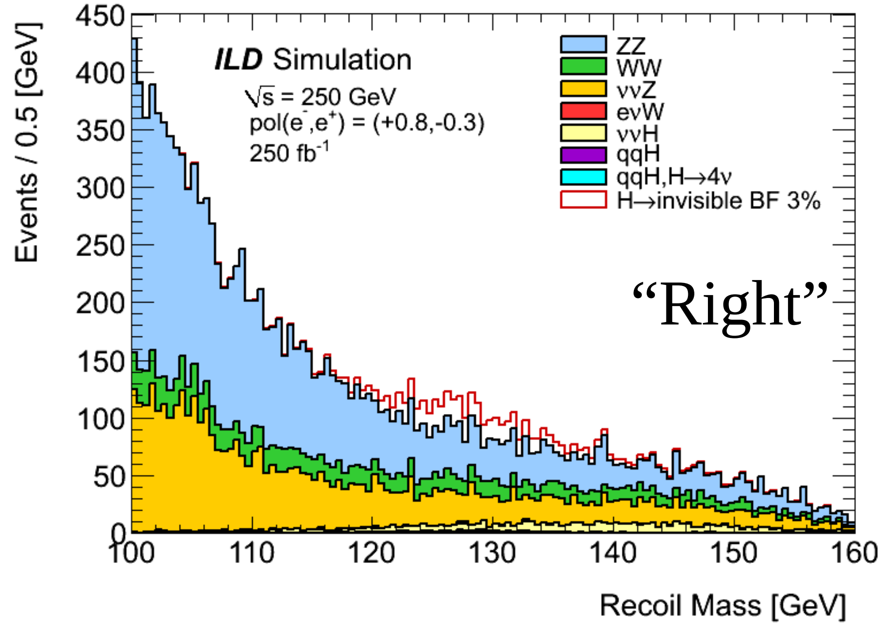
Flavor tagging very important for distinguishing different decay modes



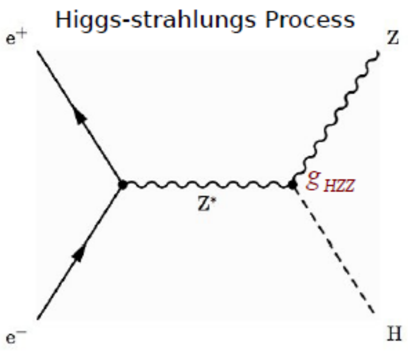
$$e^+e^- \to ZH,\ \ Z \to qq,\ \ H \to \text{invisible} \qquad \sqrt{s} = 250\ \text{GeV}$$

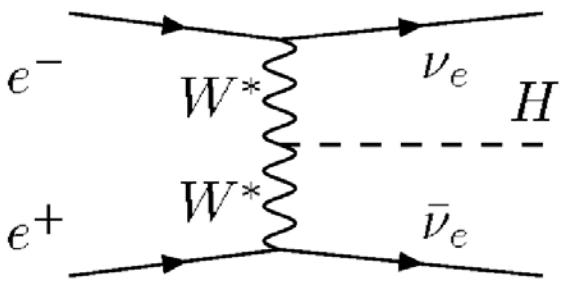
- If BF(H→invisible) = 3%
  - Signal is clearly seen for “Right” polarization





$e^+e^- \to ZH,\ \nu\nu\mathrm{H}\ \sqrt{s} = 350$ GeV



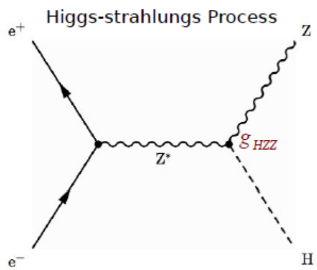


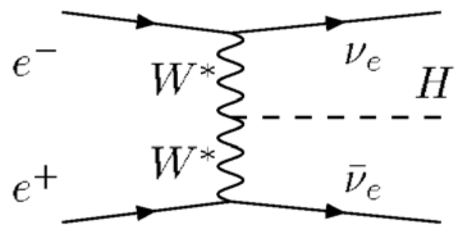
All of the Higgstrahlung studies that were done at $\sqrt{s} = 250$ GeV can also be done at $\sqrt{s} = 350$ GeV. Precisions for $\sigma \bullet BR$ are comparable, as is the precision for σ(ZH) once Z $\to q\bar{q}$ decays are included.

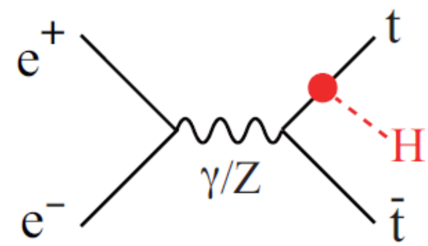
WW fusion production of the Higgs at $\sqrt{s} = 350$ GeV provides a much better measurement of g_{HWW} compared to $\sqrt{s} = 250$ GeV. This gives a much improved estimate of the total Higgs width Γ_H which in turn significantly improves the coupling errors obtained from $\sigma \bullet BR$ measurements made at $\sqrt{s} = 250$ GeV.

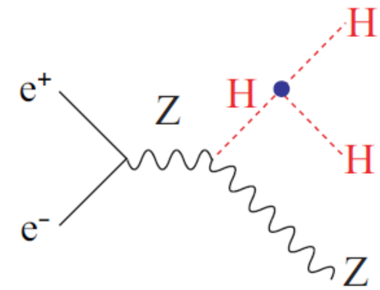
The recoil Higgs mass measurement is significantly worse at $\sqrt{s} = 350$ GeV with respect to $\sqrt{s} = 250$ GeV. However, there is hope that direct calorimeter Higgs mass measurements using $e^+e^- \to \nu\nu H$ will recover the precision.

$e^+e^- \to ZH, \nu\nu H, t\bar{t}H, ZHH \; \sqrt{s} = 500$ GeV









The g_{HWW} coupling can also be measured well at $\sqrt{s} = 500$ GeV through WW fusion production of the Higgs.

Cross section for $e^+e^- \to ttH$ significantly enhanced near threshold due to $t\bar{t}$ bound state effects. This leads to a measurement of the top Yukawa coupling $\Delta y_t / y_t = 14\%$ with 500 fb^{-1} at $\sqrt{s} = 500$ GeV.

The ZHH channel is open at $\sqrt{s} = 500$ GeV providing some sensitivity to the Higgs self coupling.

Search for additional Higgs bosons that might have been missed at LHC

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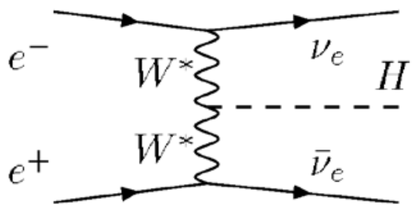
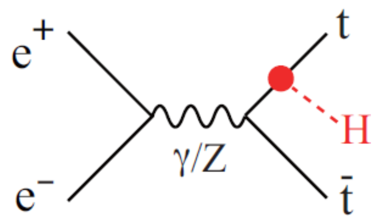
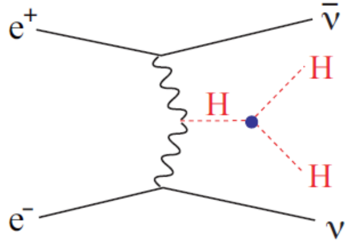
$e^+e^- \to \nu\nu H$, ttH , $\nu\nu HH$ $\sqrt{s} \geq$ 1 TeV



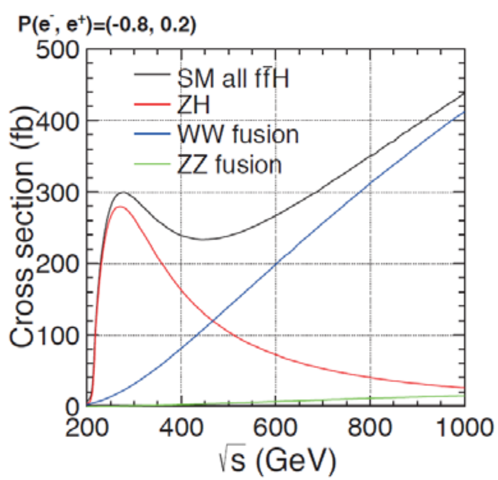




At $\sqrt{s} \geq 1$ TeV an e^+e^- collider provides better measurements of the top Yukawa coupling and Higgs self coupling.

Search for additional Higgs bosons that might have been missed at LHC.

In addition, an e^+e^- collider becomes a Higgs factory again since the total Higgs cross section is larger than the total cross sections at 250 GeV, specially if polarized beams are used:



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ILC Energy/Lumi Scenarios

- Each scenario corresponds to accumulated luminosity at a certain point in time.
- Assumption: run for $3X10^7$ s at baseline lumi at each of Ecm=250,500,1000 GeV, in that order.   Then go back and run for $3X10^7$ s at upgrade lumi at each of Ecm=250,500,1000 GeV.

Nickname	Ecm(1) (GeV)	Lumi(1) (fb^{-1})	+	Ecm(2) (GeV)	Lumi(2) (fb^{-1})	+	Ecm(3) (GeV)	Lumi(3) (fb^{-1})	Runtime (yr)	Wallplug E (MW-yr)
ILC(250)	250	250							1.1	130
ILC(500)	250	250		500	500				2.0	270
ILC(1000)	250	250		500	500		1000	1000	2.9	540
ILC(LumUp)	250	1150		500	1600		1000	2500	5.8	1220
ILC500(LumUp)	250	1150		500	1600				3.9	660

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ILC Measurement Summary

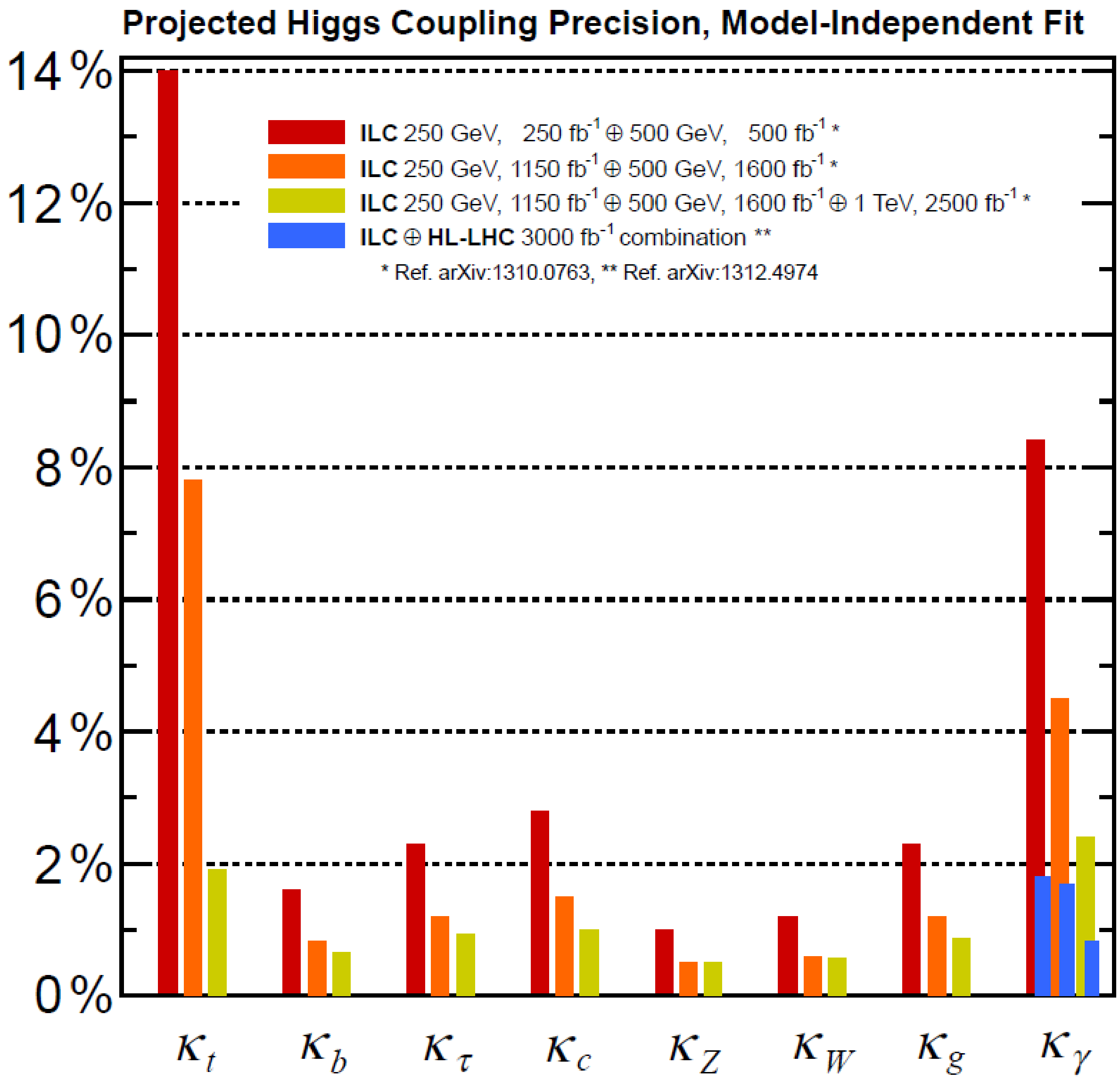
Table 5.1. Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV h boson assuming you run 3×10^7 s at the baseline differential luminosity for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)				1 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	2.6%	-	3.0	-		42.7%			26.3%
BR(invis.)	$<$ 0.9 %	-	-	-	-				
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	1.2%	10.5%	1.8%	0.7%	28%		0.5%	6.0%	
$h \to c\bar{c}$	8.3%	-	13%	6.2%			3.1%		
$h \to gg$	7.0%	-	11%	4.1%			2.3%		
$h \to WW^*$	6.4%	-	9.2%	2.4%			1.6%		
$h \to \tau^+\tau^-$	4.2%	-	5.4%	9.0%			3.1%		
$h \to ZZ^*$	19%	-	25%	8.2%			4.1%		
$h \to \gamma\gamma$	34%	-	34%	23%			8.5%		
$h \to \mu^+\mu^-$	100%	-	-	-			31%		

Table 5.2. Expected accuracies for cross section and cross section times branching ratio measurements for the 125 GeV h boson assuming you run 3×10^7 s at the sum of the baseline and upgrade differential luminosities for each center of mass energy. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	1150 fb^{-1} at 250 GeV (-0.8,+0.3)		1600 fb^{-1} at 500 GeV (-0.8,+0.3)				2.5 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	1.2%	-	1.7	-		23.7%			16.7%
BR(invis.)	$<$ 0.4 %	-	-	-			-		
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.6%	4.9%	1.0%	0.4%	16%		0.3%	3.8%	
$h \to c\bar{c}$	3.9%	-	7.2%	3.5%			2.0%		
$h \to gg$	3.3%	-	6.0%	2.3%			1.4%		
$h \to WW^*$	3.0%	-	5.1%	1.3%			1.0%		
$h \to \tau^+\tau^-$	2.0%	-	3.0%	5.0%			2.0%		
$h \to ZZ^*$	8.8%	-	14%	4.6%			2.6%		
$h \to \gamma\gamma$	16%	-	19%	13%			5.4%		
$h \to \mu^+\mu^-$	46.6%	-	-	-			20%		

ILC Model Independent Higgs Coupling



$\Delta\Gamma_{tot}$ = 4.9%

2.5%

2.3%

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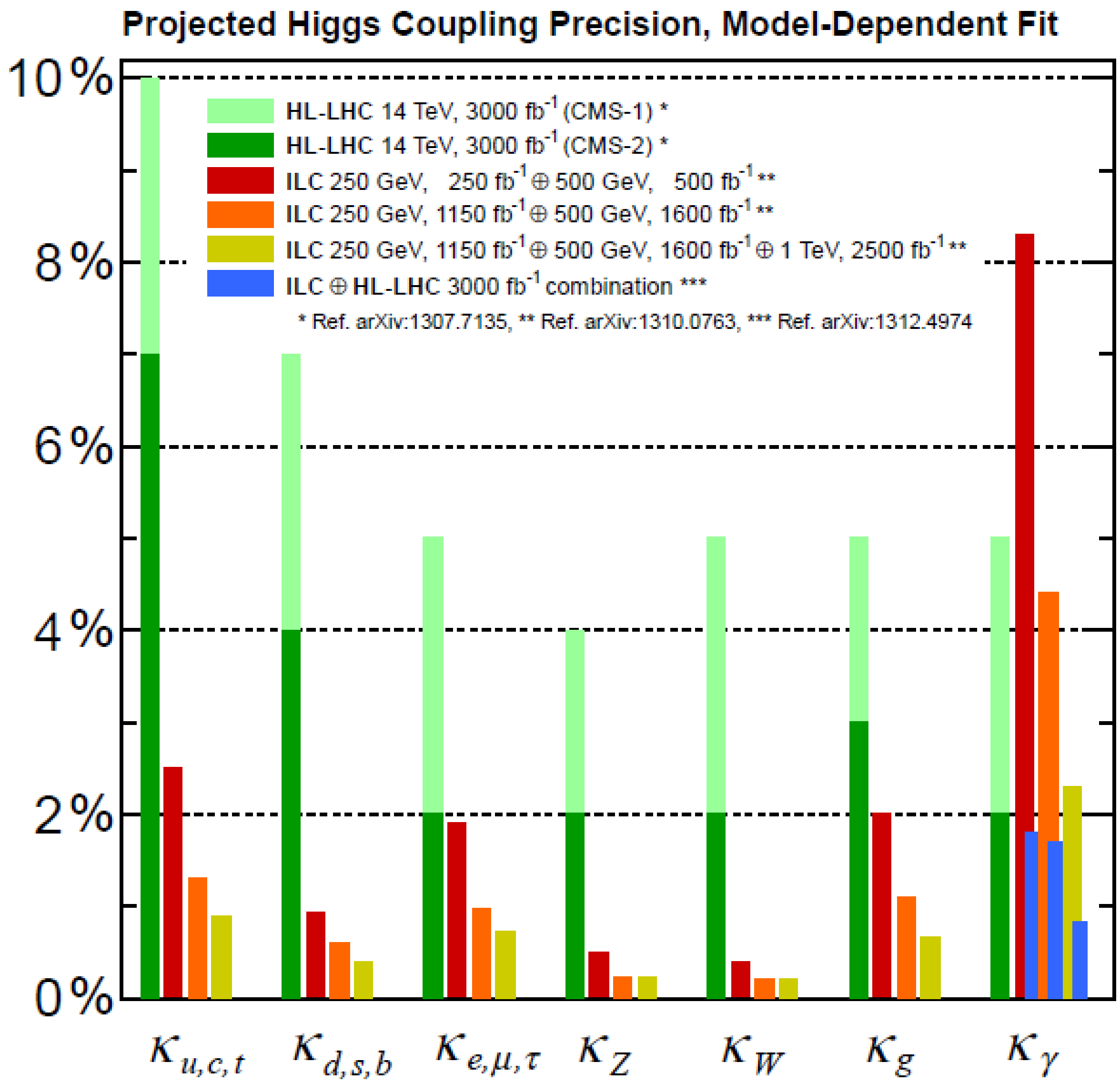
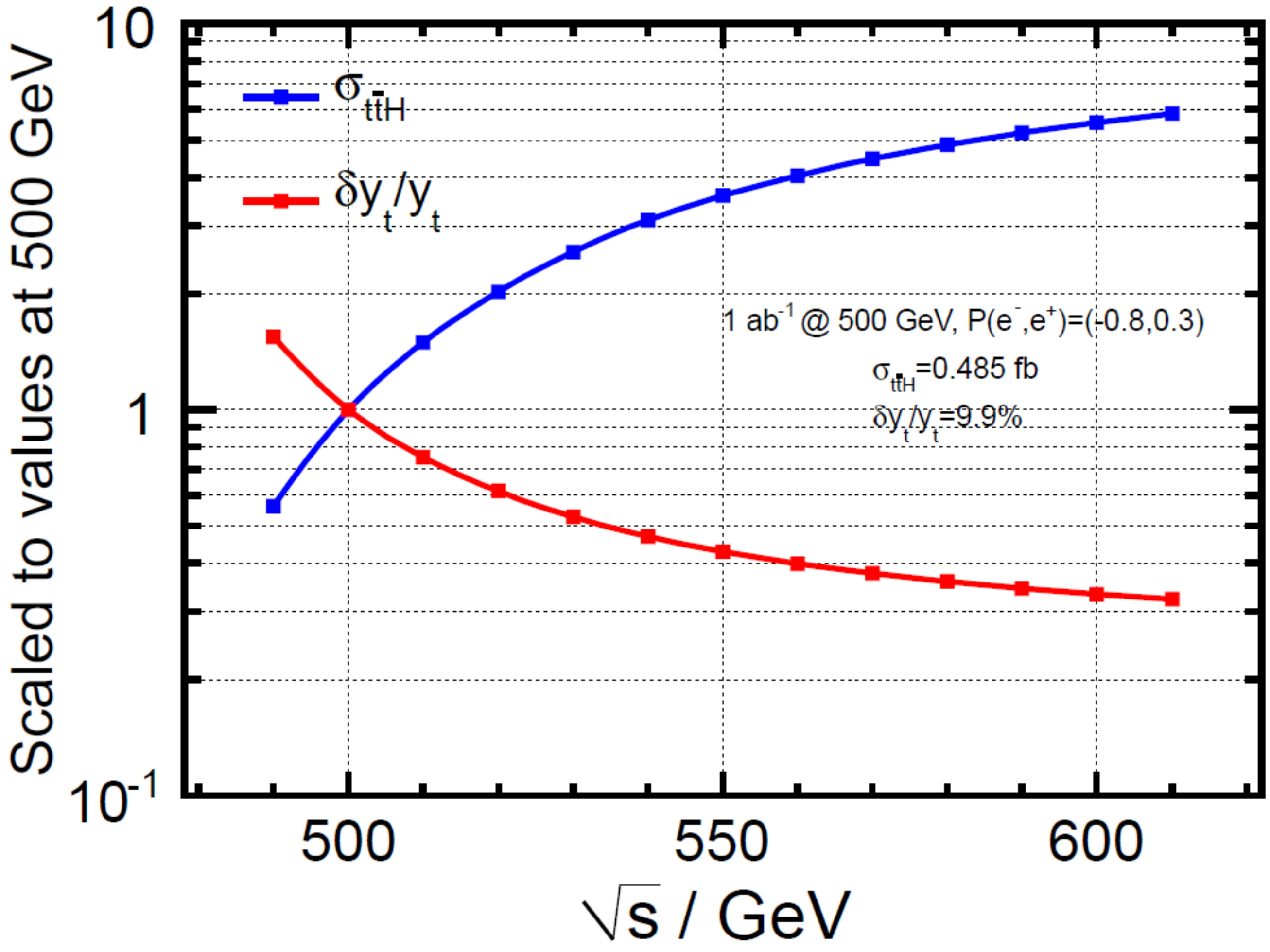
Higgs Coupling Comparison Between LHC and ILC

7 Parameter HXSWG Benchmark



Top Yukawa Coupling Versus $\sqrt{s}$



Precision improves by more than a factor of 3
going from 500 to 550 GeV

Higgs Self Coupling Summary

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-0.8,0)$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10%

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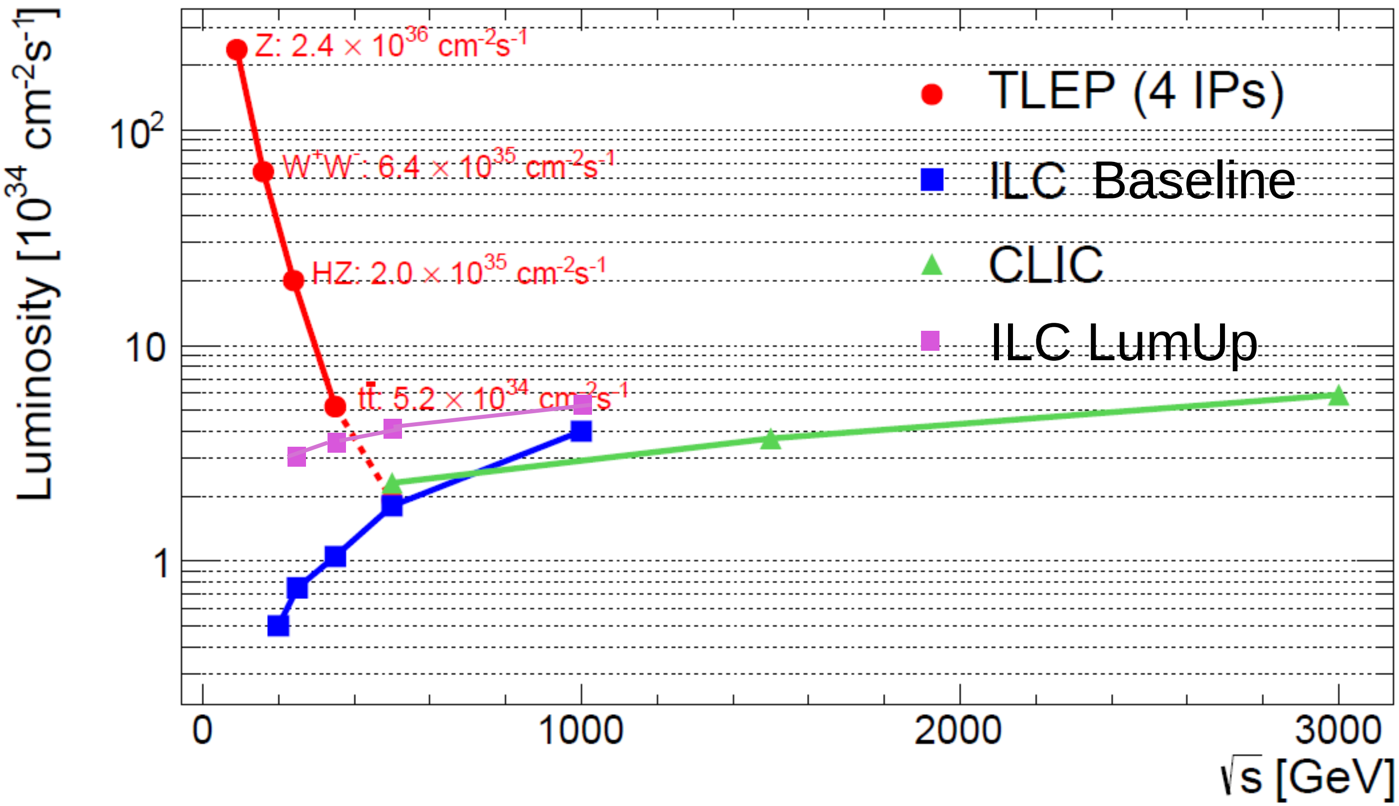
FCC−ee



2 Big Luminosity Advantages of FCC-ee over ILC:

- 4 IP's
- Luminosity of FCC-ee grows as $\sqrt{s}$ is lowered below 250, while ILC luminosity drops off

Model Dependent Fits (7 Parameter HXSWG Benchmark)

Numbers from "First Look at Physics Case for TLEP", JHEP 01,164(2014) TLEP = 4 exp. @ 240 +350 GeV

Numbers from ILC Higgs White Paper, arXiv:1310.0763,

Coupling	TLEP	ILC500(LumUp)*
g_{HZZ}	0.05%	0.3%
g_{HWW}	0.09%	0.3%
g_{Hbb}	0.19%	0.6%
g_{Hcc}	0.68%	1.4%
g_{Hgg}	0.79%	1.1%
$g_{H\tau\tau}$	0.49%	1.0%
$g_{H\mu\mu}$	6.2%	42%
$g_{H\gamma\gamma}$	1.4%	4.4%

* Includes several 0.1% systematic errors including 0.1% theory error

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Model Independent fits

Numbers from "First Look at Physics Case for TLEP", JHEP 01,164(2014)
TLEP = 4 exp. @ 240 +350 GeV

Numbers from ILC Higgs White Paper, arXiv:1310.0763,

Coupling	TLEP-240	TLEP	ILC500(LumUp)
g_{HZZ}	0.16%	**0.15%**	0.5%
g_{HWW}	0.85%	**0.19%**	0.6%
g_{Hbb}	0.88%	**0.42%**	0.8%
g_{Hcc}	1.0%	**0.71%**	1.5%
g_{Hgg}	1.1%	**0.80%**	1.2%
$g_{H\tau\tau}$	0.94%	**0.54%**	1.2%
$g_{H\mu\mu}$	6.4%	**6.2%**	42%
$g_{H\gamma\gamma}$	1.7%	**1.5%**	4.5%

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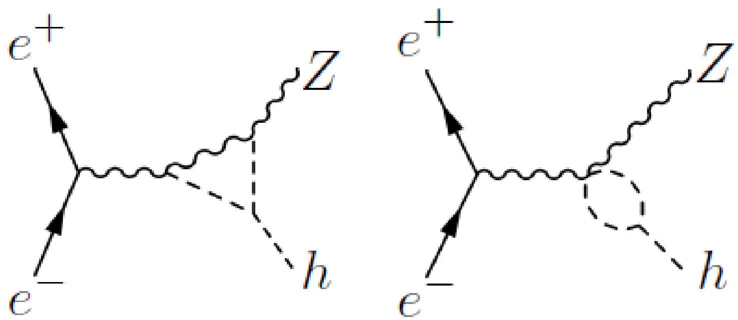
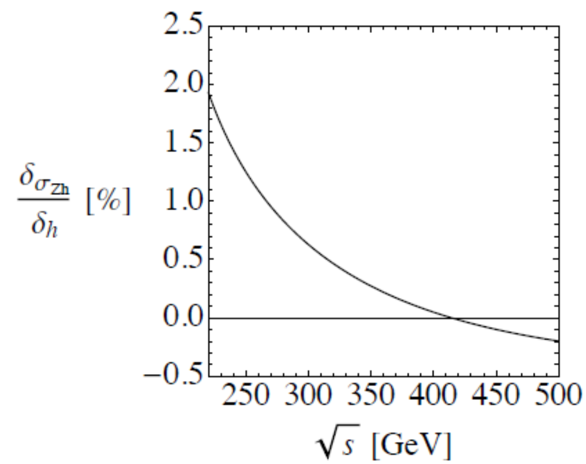
Higgs Self Coupling Measurement at FCC-ee Using NLO Contribution to $e^+e^- \to ZH$ at $\sqrt{s} = 240\ \&\ 350$ GeV

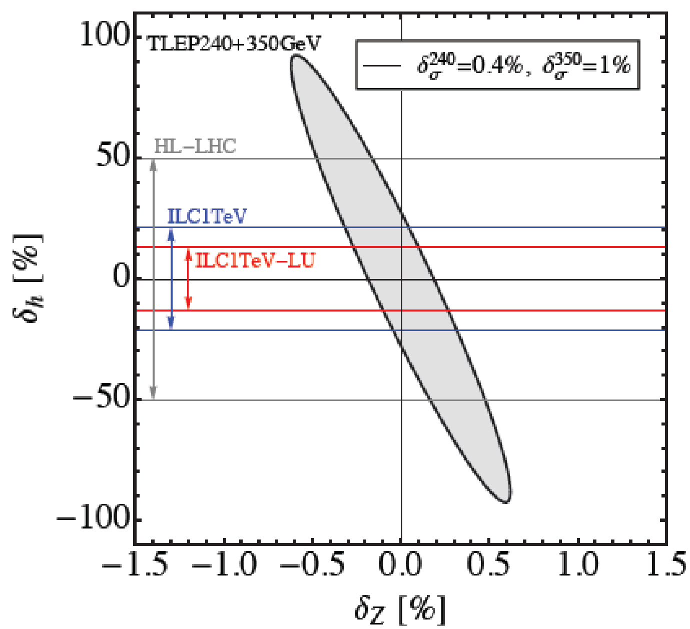
M. McCullough, arXiv:1312.3322





$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

Assuming $\delta_Z = 0$ Higgs self coupling can be constrained to $|\delta_H| < 28\%$ by FCC-ee at $\sqrt{s} = 240$ GeV



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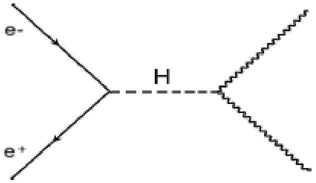
FCC-ee

Measurement of Electron Yukawa Coupling @ $\sqrt{s} = 125$ GeV?

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



$\sigma(e^+e^- \to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^- \to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

- Signal + backgrounds study for 7 decay channels:
  WW*(2j,lν) (σ = 28 ab), WW*(2l2ν) (σ = 6.7 ab),
  WW*(4j) (σ = 29.5 ab), ZZ*(2j2ν) (σ = 2.3 ab), ZZ*(2l2j) (σ = 1.14 ab),
  bb (2j) (σ = 156 ab), gg (2j) (σ = 24 ab)
- Preliminary analysis:
  $L_{int} = 10\ ab^{-1}$, S=0.65: BR(Hee) < 4.63×BR_{SM} (3σ), $g_{hee} < 2.15 \times g_{Hee,SM}$ (3σ)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: H→ bb, H → WW → 4j
- Challenging accelerator conditions: mono-chromaticity, huge lumi

Summary

- Due to the unique experimental environment of e^+e^- machines, ILC, CLIC and FCC-ee can improve on the excellent Higgs measurements expected from LHC and HL-LHC. They provide a means to bring Higgs coupling precisions from the few percent level to the sub-percent level
- The ILC – the most mature of the future e^+e^- designs – provides significant improvement over HL-LHC over a wide range of Higgs couplings.
- CLIC and FCC-ee can take the Higgs coupling measurements even further, with significant enhancements in energy and luminosity, respectively, relative to the ILC.

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